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# AEROBRAKING AT VENUS AND MARS: A COMPARISON OF THE MAGELLAN AND MARS GLOBAL SURVEYOR AEROBRAKING PHASES.

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Abstract:

Two interplanetary spacecraft have been successfully aerobraked from elliptical initial orbits to nearly circular final orbits. The Magellan orbit about Venus was circularized in 1993, late in the extended mission. The Mars Global Surveyor spacecraft achieved a circular orbit about Mars in February 1999. The aerobraking phase of the Mars Global Surveyor mission was severly complicated when one of the solar panel was damaged during initial deployment. This paper will discuss some of the similarities and differences between these two aerobraking missions.

## INTRODUCTION:

This paper will compare the aerobraking phases of the Magellan and Mars Global Surveyor (MGS) missions. A short summary of each mission will be given, followed by a detailed comparison of the more important aspects related to aerobraking.

### Magellan Mission Summary:

The Magellan spacecraft[1-13] was launched on the space shuttle Atlantis on May 4, 1989 and injected toward Venus on a Type 4 trajectory by an IUS upper stage. Magellan was propulsively captured into a 8,459 km by 290 km (3.26 hour) elliptical orbit around Venus on Aug. 10, 1990 using a Star 48 solid rocket motor. During the next 2 years and 9 months the Magellan spacecraft went on to obtain a global map of the surface by using a synthetic array radar to penetrate the dense cloud cover. It also obtained a nearly global altimetry map and a high resolution gravity map of the equatorial region. During an aerobraking phase from May 25 to August 3, 1993, Magellan used atmospheric drag to remove 1200 m/s from the orbit to achieve a nearly circular, 541 km 197 km (1.57 hour) orbit, in order to obtain a high resolution global gravity map of Venus during the remainder of the mission. Magellan crashed into Venus on Oct. 12, 1994, on orbit 15038.

The inset at the upper right of Figure 1 shows the Magellan spacecraft in the aerodynamically stable aerobraking configuration, with the -Z axis into the flow. The "bowl shape" at the top is the High Gain Antenna (HGA). The altimeter antenna is the triangle on the left side of the HGA. The two solar panels, viewed edge-on, are along the X-axis of the spacecraft. The thrusters are located in 4 modules mounted on struts near the bottom of the spacecraft. The radar electronics are in the long rectangular box in the middle, while most of the spacecraft electronics are mounted in bays near the bottom of the spacecraft. The "shading" around the spacecraft is meant to represent atmospheric molecules, while the "white space" has been swept clear by the the spacecraft HGA and solar panels.

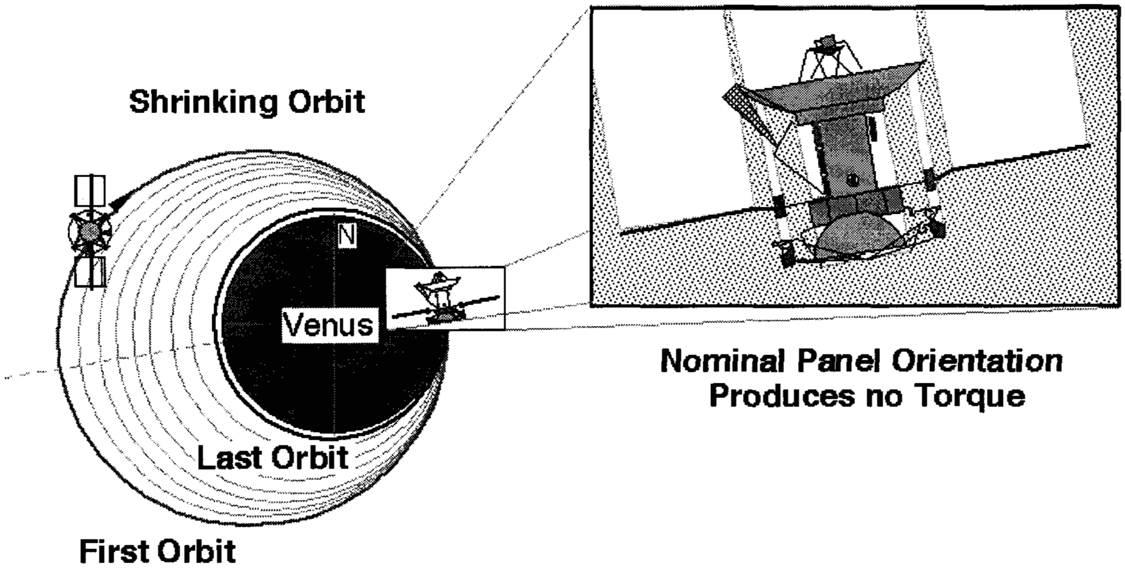


Figure 1: Magellan Spacecraft in Aerobraking Configuration

Mars Global Surveyor Mission Summary:

The Mars Global Surveyor (MGS) spacecraft[14-25] was launched on a Delta 7925 from the Kennedy Space Center on Nov. 7, 1996. Shortly after launch, telemetry indicated that one of the two solar "panels" had not locked up completely. An extensive analysis campaign during the cruise to Mars was able to find a new panel configuration that could be used for propulsive maneuvers with the unlatched panel. MGS was successfully captured into a highly elliptical 54,026 km by 263 km (45 hour) orbit around Mars on September 11, 1997. The analysis indicated that a damper mechanism had broken, such that the damper arm had wedged between the yoke and the inner gimbal, preventing the panel from latching[19]. Aerobraking began as originally planned, except that the unlatched panel was rotated 180° about the inner gimbal to put the cell side into the flow such that the aerodynamic torques would push the unlatched hinge toward the closed position. After only 11 aerobraking orbits, it became clear that the damage which had occurred at deployment of the solar panel was much more serious than an unlatched hinge. The solar panel was bending beyond the fully closed position, an impossible situation. Aerobraking was halted during an 18 orbit hiatus that started on orbit 19 while the situation was reevaluated. The aerobraking phase of the mission was completely replanned while the new data were evaluated to determine what aerodynamic torques, if any, could be safely used. The analysis and concurrent ground testing indicated that one of the face sheets on the yoke had been seriously cracked when the undamped panel slammed open. The apparent bending moment was being provided by a single facesheet on the yoke. Ground testing indicated that an undamaged facesheet could survive hundreds of bending cycles at low levels, so aerobraking was resumed at a dynamic pressure that was less than half the value that was originally planned. Aerobraking resumed on orbit 37 (Nov. 8, 1997) with a new target orbit of 2 am, rather than 2 pm local solar time[14].

Figure 2 shows the MGS spacecraft in the aerodynamically stable aerobraking configuration. The thrusters are in four modules at the ends of the projections near the bottom (-Z end) of the spacecraft. The bi-propellant main engine is along the centerline.

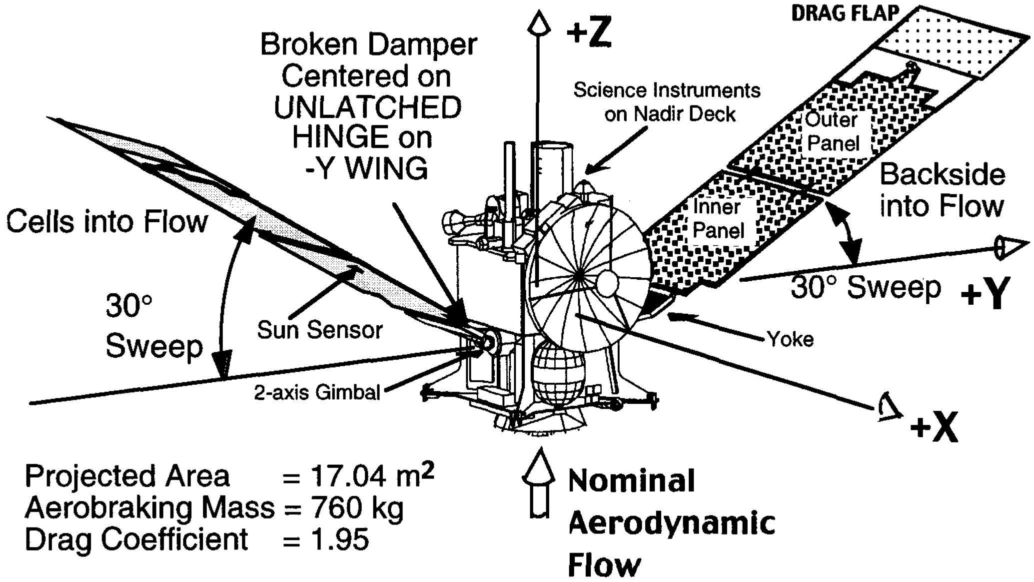


Figure 2: Mars Global Surveyor (MGS) Spacecraft in Aerobraking Configuration.

A small dust storm in the southern hemisphere caused the atmospheric density to increase rapidly on orbit 51 (Nov. 28, 1997), which required the MGS periapsis altitude to be raised suddenly to avoid damage to the spacecraft. Aerobraking continued until orbit 201 (March 27, 1998), where aerobraking was temporarily halted in an 11.5 hour orbit to wait for Mars to pass through the communications blackout around Solar conjunction. Science data were collected during this "Science Phasing Orbit", where the spacecraft remained in the slowly precessing 11.5 hour orbit until the Sun arrived at the desired orientation needed to achieve the final Sun synchronous orbit. Phase 2 of aerobraking began on orbit 574 (Sept. 24, 1998) and concluded on orbit 1284 (Feb. 4, 1999) with the successful completion of aerobraking. MGS was propulsively inserted into the desired 434.7 km by 370.5 km mapping orbit on March 9, 1999. Since the damper on the High Gain Antenna (HGA) was the same design as the one which failed during the solar panel deployment, the HGA was not deployed until after 30 days of science data had been taken from the mapping orbit. The HGA was deployed successfully, and the MGS spacecraft began normal mapping operations one year later than originally planned.

Mars Global Surveyor is currently mapping Mars. Hypertext links to the recent data and images can be found at http://mars.jpl.nasa.gov/.

## COMPARISON OF THE AEROBRAKING PHASES:

The aerobraking phase of the Magellan mission[1-4] to Venus will be compared to the actual and planned aerobraking phases of the Mars Global Surveyor mission[14-20] to Mars. Both missions gradually lowered periapsis in several steps (the Walk-in phase) in order to accommodate uncertainties in the atmospheric models. Both missions had a main phase, where most of the orbit period reduction occurred. Both missions had a walkout phase, where the rate of orbit decay was reduced near the end of aerobraking. Only the MGS mission had an orbit lifetime constraint of 2 days which was designed to give the project time to recover from a safing event near the end of the aerobraking phase. The original MGS plan called for a 3 day orbit lifetime, which was eventually reduced to 2 days because the 3 day constraint added too many days and orbits to the end of aerobraking. The 2 day constraint was only adopted when the Mars Surveyor Operations

Project was convinced that recovery from safing could be achieved in less than 2 days. Although the average dynamic pressure at the end of the Magellan aerobraking phase at Venus was reduced from .35 to .22 N/m$^2$, this was to compensate for the longer aerodynamic heating duration for the final orbits rather than to maintain a certain orbit lifetime. A series of 5 maneuvers were used to raise the Magellan periapsis out of the atmosphere, because the small attitude control thrusters were used to provide the 15 m/s, and a single burn was too long for an inertial maneuver. On the other hand, MGS used the attitude control thrusters during the Walkout, to maintain the 2 days orbit lifetime, but used a single bi-propellant main engine maneuver to exit the atmosphere.

Because one of the solar array yokes on the Mars Global Surveyor spacecraft was damaged during deployment, some aspects of the MGS mission had to be changed, which makes a comparison of the the Magellan and Mars Global Surveyor missions more difficult. The actual values as flown will be discussed, but the original MGS plan will also be mentioned so that the reader does not go away with a sense that aerobraking at Mars is necessarily a longer process than aerobraking at Venus. About 1200 m/s was removed from the velocity at periapsis for both spacecraft. For the Magellan mission aerobraking took 70 days and 730 orbits. For the MGS spacecraft, aerobraking required 298 days and 890 orbits, plus an additional 25 day hiatus, to replan the mission due to a broken solar panel yoke, and another 180 day break in aerobraking to allow the orbit to reach an orientation relative to the Sun (2 am local solar time at the descending node) equivalent to the originally planned 2 pm orbit. The prelaunch MGS aerobraking plan only required 130 days and 405 orbits. The reason that the original MGS aerobraking plan required almost twice as much time as Magellan was due to the fact that the planned initial MGS orbit period was 48 hours, whereas the initial Magellan orbit period was only 3.26 hours, so there were more drag passes per day for Magellan. (Figure 3 shows a comparison of the orbit period during aerobraking.)

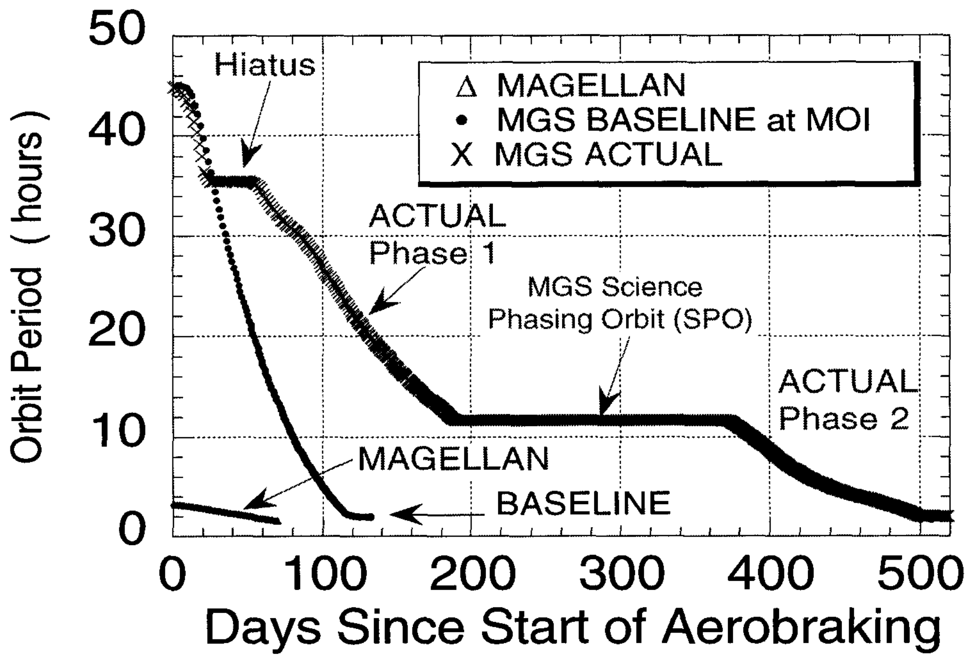


Figure 3: Orbit Periods during Aerobraking for Magellan and MGS.

The original MGS plan required only 60% as many orbits as Magellan because the velocity at periapsis at Mars is only about half as fast as the velocity at periapsis at Venus, as shown in Figure 4. Since the free stream heating rate, $0.5\ \rho\ V^3$, is proportional to the cube of the velocity, while the dynamic pressure is proportional to the square of the velocity, a similar heating rate limit results in a dynamic pressure limit at Mars that is twice as large as that at Venus, and thus only requires half as many orbits to remove a similar amount of velocity from the trajectory.

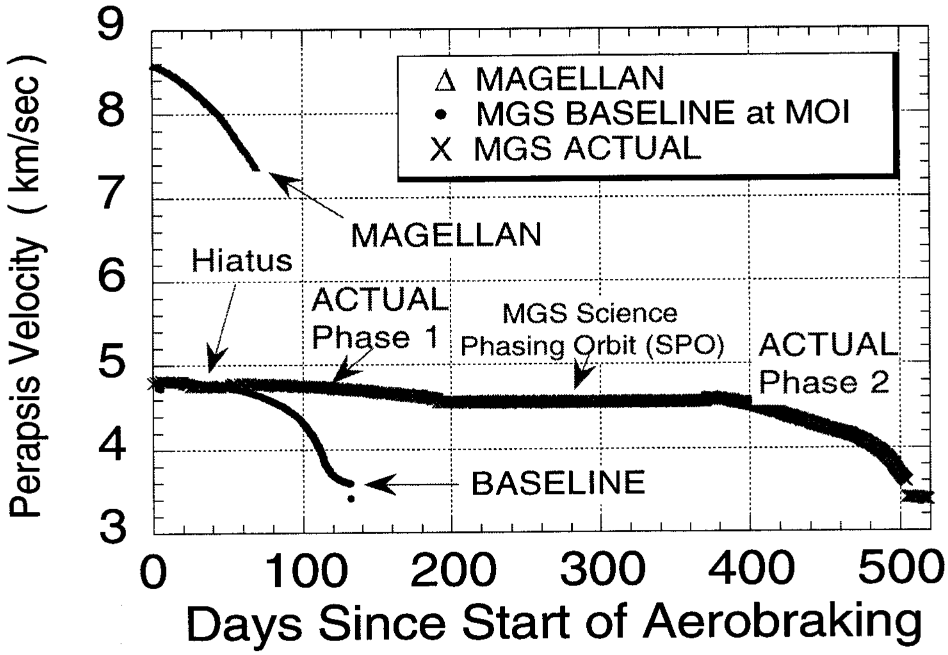


Figure 4: Periapsis Velocity during Aerobraking for Magellan and MGS.

Dynamic Pressure Control Corridor:

Maneuvers to raise or lower periapsis for Magellan[5,6] and MGS[19,20] were triggered based on the dynamic pressure trend. The dynamic pressure ($DP = 0.5\ \rho\ V^2$) at periapsis for the original MGS plan was in the range of 0.45 - 0.60 $N/m^2$ (for launch near the open of the launch period), whereas the actual dynamic pressure range was 0.10 - 0.35 $N/m^2$. Figure 5 is a comparison of the dynamic pressure at periapsis for Magellan and MGS. The actual Magellan data was inferred from Navigation reconstructions of the orbit based on tracking data from every orbit and plotted using Green "Δ". (The data ends on Day 70, at the completion of aerobraking). The computer simulated MGS pre-MOI Baseline data is plotted using Blue "•" (ending on Day 130). The actual MGS data in Figures 5 and 6 is based on the Navigation reconstruction of the orbit from tracking data and is plotted using Red "X" (ending on Day 520). The MGS navigation reconstruction, which is in good agreement with the accelerometer data, is used to be consistent with the Magellan data.

The dynamic pressure range in the pre-MOI Baseline plan was the result of keeping the expected aerodynamic heating[21] ($Qdot = 0.5\ \rho\ V^3$) less than 0.4 $W/cm^2$ at periapsis to maintain more than 100% margin for unpredictable increases in the atmospheric density. The actual MGS dynamic pressure limits were designed to keep the broken solar panel from bending more than a few degrees during the drag pass[19]. Figure 6 shows Qdot at periapsis. The low values in the actual MGS data starting at Day 65 coincide with the start of the dust storm, where periapsis was raised to a higher altitude to protect the spacecraft in case the density continued to increase.

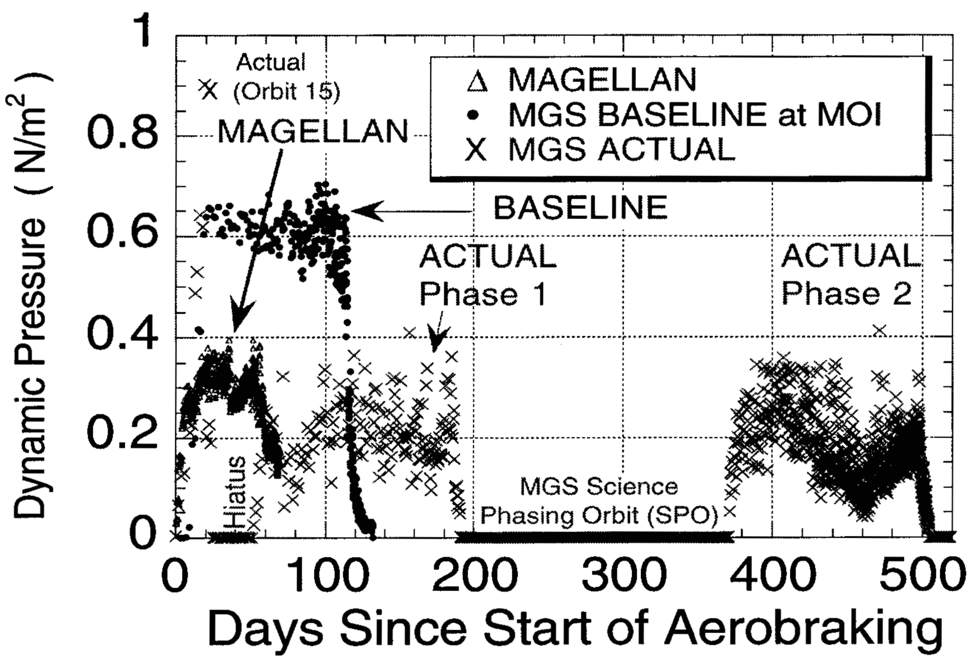


Figure 5: Dynamic Pressures during Aerobraking for Magellan and MGS.

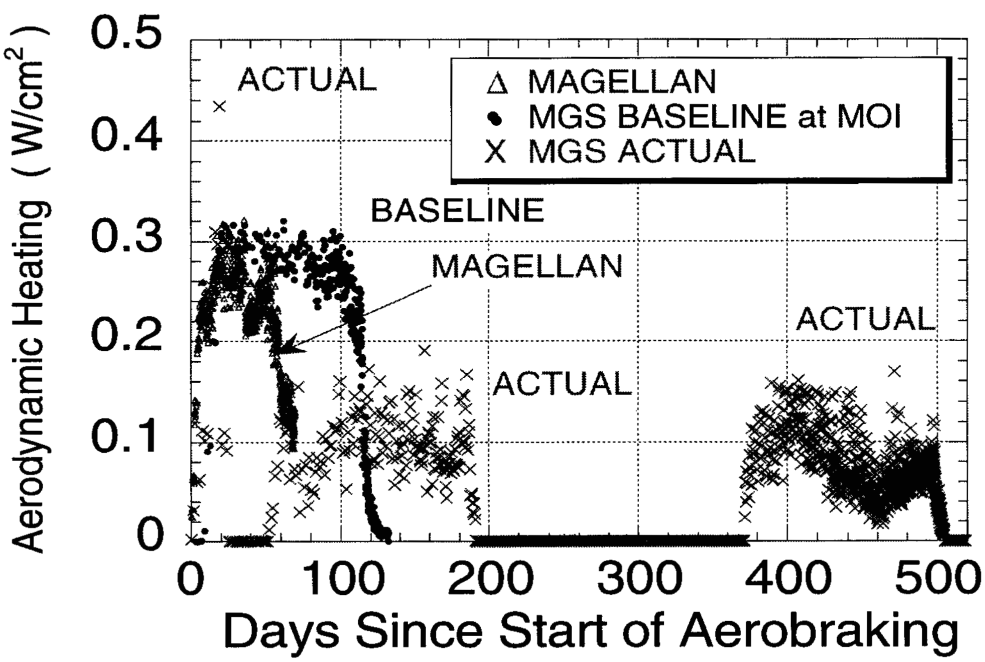


Figure 6: Free Stream Aerodynamic Heating Rates during Aerobraking

For Magellan, a heating rate limit was initially used during the early design phases, however, a dynamic pressure constraint was introduced to try to keep the attitude rates small in case of a sideways entry in the event the spacecraft went into safe mode during aerobraking. A sideways entry at a high dynamic pressure would have resulted in a body rate large enough to saturate the gyros, and result in loss of attitude knowledge and probably the loss of the spacecraft. (The MGS gyros did not have this limitation.) Although the Magellan mission eventually waived the requirement to keep the body rates for the worst case (safing) attitude below the gyro saturation limit because the aerobraking duration would have been too long, the dynamic pressure limit was kept as the control parameter for aerobraking operations. Maintaining a constant dynamic pressure results in decreasing aerodynamic heating as the velocity at periapsis decreases as aerobraking progresses, which partially compensates for the longer heating durations as the orbit becomes more circular. Thus both Magellan and MGS controlled the periapsis altitude based on the observed dynamic pressure during operations, even though heating rate was initially the control parameter early in the design phase for both missions.

On-Board Sequence of Events:

The sequence of events in a typical aerobraking orbit were similar near periapsis for both missions, but different elsewhere. Near periapsis, the solar panels for both spacecraft had to be configured for the drag pass, and both spacecraft had to be turned to enter the atmosphere "tail-first", with the aerodynamically stable attitude more or less aligned with the velocity vector. The dead band limits were set to large values, and thrusters were used to control the attitude during the drag pass for both spacecraft.. Time margin was allocated to both sides of the expected drag pass to account for timing uncertainties, which are primarily due to the uncertainties in the atmospheric density. Telemetry data during the drag pass were recorded for later playback, because neither spacecraft could maintain a real time link with Earth while in the drag attitude. After leaving the atmosphere, both spacecraft would null out residual attitude errors and rates before switching back to reaction wheel control for the remainder of the orbit. Since the MGS High Gain Antenna (HGA) was not deployed until after aerobraking was completed, and since all of the Magellan antennas were body-fixed, both spacecraft had to turn and point the HGA toward the Earth to playback the critical telemetry data recorded during the drag pass. Both vehicles recorded temperatures, attitude positions and rates, however, MGS was also able to record accelerations from an accelerometer built into the Inertial Measurement Unit. Magellan did not carry any accelerometers. Near apoapsis of some orbits, both spacecraft had to be able to perform a propulsive maneuver to control the periapsis altitude in order to maintain the appropriate drag levels on the upcoming orbits.

The Magellan sequence of events included an extra maneuver to accommodate degrading thermal performance. During the part of the orbit between apoapsis and the turn to the drag attitude, the Magellan spacecraft pointed the HGA toward the Sun for use as a thermal shield to keep the temperature of the electronics within an acceptable range. The MGS spacecraft was able to stay Earth pointed during the entire non-drag part of the orbit, except during propulsive maneuvers. Another difference was that while Earth pointed, the MGS spacecraft would rotate slowly about the HGA boresight in order to sweep the body-fixed star scanner along a band of stars to maintain inertial attitude knowledge. The Magellan spacecraft maintained a nearly inertial attitude while Earth pointed. The Magellan spacecraft performed a special maneuver at apoapsis every other orbit to sweep its body-fixed star scanner across two specific stars, which were selected periodically from a short list of stars that could be detected by the hardware.

Uncertainties in the time of periapsis required frequent last minute "tweaks" to the Deep Space Network (DSN) tracking schedules[13], which are normally determined days in advance.

Science Measurements while Aerobraking:

By the time that Magellan aerobraking took place late in the extended mission, the primary science instrument was no longer being used. MGS aerobraking took place before the start of the primary science mission, so there was a strong desire to collect as much science data along the way as possible. During phase 1 of MGS aerobraking, Thermal Emission Spectrometer (TES) data were collected during the drag pass and during Earth pointing using the pointing mirror built into the TES instrument. Image data were collected just after each drag pass by rolling MGS about the Y-axis in order to slew the Mars Orbiter Camera (MOC) across Mars. An additional playback for science data was scheduled every orbit during phase 1 for MGS, whereas, Magellan only had to play back telemetry data.

One of the primary drivers for taking MGS science data during an already intense operational period was the fact that dust storms frequently perturb the Martian atmosphere[23-25]. The atmosphere of Venus is so thick near the surface that high winds are not possible, so even if Magellan had the capability to collect science data near the surface, such data were not needed during operations. During a Martian dust storm, wind distributes dust through the atmosphere both horizontally and vertically. Although the dust never gets high enough to directly contact the spacecraft, it absorbs solar heat more readily than a clear atmosphere, which means that the middle atmosphere gets warmer when dust is present. Warming the middle atmosphere causes it to expand, which increases the density everywhere above, even at the aerobraking altitudes. The danger occurs right at the start of a large global dust storm, when the atmosphere is transitioning from clear and cold to dusty, warm, and expanded. Global Circulation models indicate that the density at aerobraking altitudes can increase by a factor of 10 in only a few days. Since the MGS spacecraft was going to fly at a density where there was only a factor of 2 margin, it was critically important that the onset of a global dust storm be detected promptly so that the periapsis altitude could be raised propulsively before the density had time to increase by more than a factor of 2. Some of the on-board sciece instruments, primarily the TES and the MOC, could detect dust in the atmosphere, which made collection of science data during aerobraking important operationally as well as scientifically. The science data were most important early in the aerobraking phase where the time between drag passes was as long as 2 days. In fact, a small dust storm was detected early in the MGS aerobraking phase, and periapsis was raised to accommodate the density change. Even this relatively small dust storm was able to change the density by 133% in 32 hours (one orbit). The Magellan mission to Venus did not have to worry about either sudden density increases due to dust storms or long times between orbits for atmospheric changes to develop.

Dust storms will be a consideration for future Mars missions that use aerobraking. For example, the Mars Climate Orbiter that will arrive at Mars in September (1999) plans to use the real time data from MGS to monitor the Martian atmosphere, because its own instruments will not be available for use until after aerobraking is complete. If the MGS data were not available, the Mars Climate Orbiter could not aerobrake as rapidly as currently planned - especially since the Mars Climate Orbiter aerobraking phase occurs during the dust storm season near perihelion, when most of the large dust storms have been observed.

Spacecraft Hardware:

The spacecraft hardware for both spacecraft was similar in many respects. Both vehicles were 3-axis stabilized using reaction wheels with monopropellant Attitude Control (ACS) thrusters for maneuvers and momentum unloading. Solar power was collected by articulated solar panels and stored in batteries. Telecom during aerobraking was primarily through a body-fixed High Gain antenna. Emergency communication was provided by low gain antennas. Both spacecraft pointed the Z-axis of the spacecraft toward the central planet to collect science data. The MGS spacecraft had a bi-propellant system, that was used to perform larger maneuvers, and the solar panels were gimballed about two axes instead of just one. The MGS batteries were Nickle-Hydrogen, while the Magellan batteries were NiCad. The Magellan spacecraft had a Medium Gain Antenna and an altimeter antenna.

Attitude Control:

Attitude Control during the drag pass[7,8] was based on the same philosophy for both spacecraft: Don't waste propellant fighting the aerodynamics[11,12,21]. The aerodynamically stable null attitude was more or less aligned with the velocity vector near the start of the drag pass to minimize the amplitude of the undamped oscillation about the aerodynamic null during the drag pass. Since the aerodynamic moments at large angles of attack were larger than the thruster control torque for both spacecraft, and since the timing error due to atmospheric uncertainties on previous orbits would normally result in a noticeable difference between the reference attitude and the actual attitude, trying to maintain tight attitude control during the drag pass would not only have been unsuccessful, but would have wasted considerable propellant in the process. Since reaction wheel control laws are usually proportional to the error, it was easier to adapt the existing thruster control law to aerobraking by choosing very wide (≈17°) position deadbands with a similarly large limit for the rate.

Figure 7 shows a plot of the Magellan attitude error about the X-axis. Because there was a large deadband, the spacecraft oscillated about the aerodynamic null when the spacecraft was in the atmosphere. For Magellan, a large oscillation amplitude was about ±2.5°, whereas for MGS, a large oscillation amplitude was about ±4°. The amplitude of the oscillation primarily depended on the angle of attack at atmospheric entry. Since the attitude reference for both missions was a time

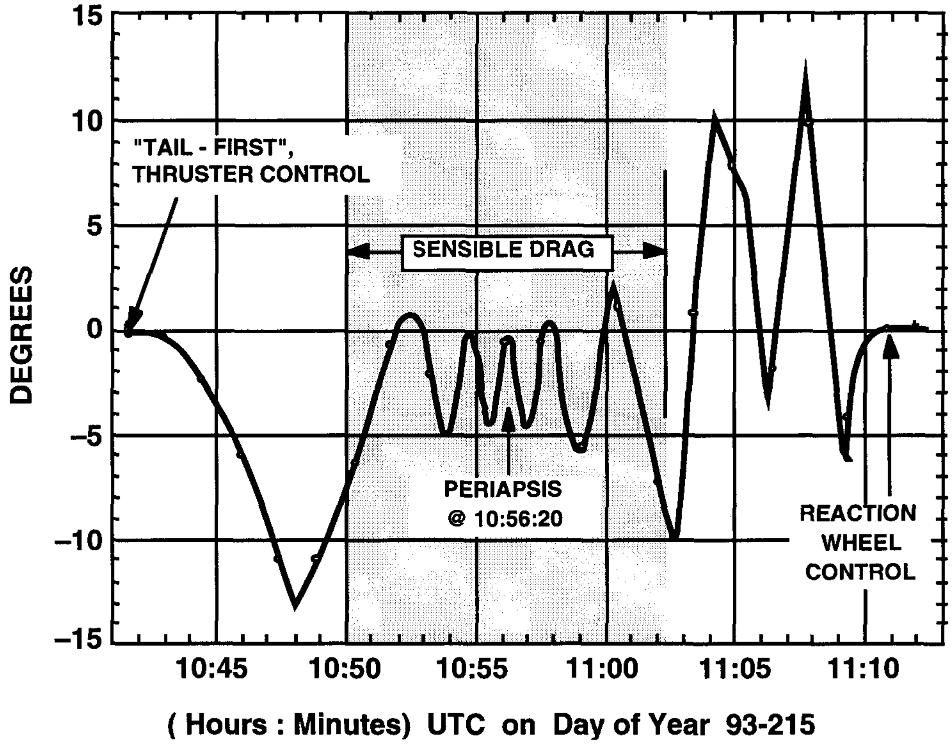


Figure 7: Magellan X-axis Attitude Error During the Drag Pass.

varying function of the predicted time since periapsis, the error for the axis orthogonal to the orbit plane (Magellan X, MGS Y) was sensitive to timing errors. Thus the center of the oscillation was offset from zero by an amount proportional to the timing error. Once the spacecraft left the atmosphere, aerodynamics no longer held the attitude near the reference and the residual rate caused the error to build up until the spacecraft hit the deadband limit. From that point on, the spacecraft "bounces" from one side of the deadband to the other when the thrusters fire. Most of the Attitude Control propellant is used during this phase, just after the drag pass. One of the differences between Magellan and MGS was the fact that the MGS thruster control algorithm was designed to include some damping, whereas the Magellan algorithm was adapted by increasing the deadband parameter tables, and was not as efficient.

One difference between the Magellan and MGS Attitude Control Systems is the fact that the MGS reaction wheels could be commanded to maintain a constant speed, whereas the Magellan reaction wheels would gradually spin down due to friction when the spacecraft switched to thruster control. The angular momentum from the Magellan wheels was transferred to the spacecraft body, causing it to spin slowly. Although the angular rate was small, there was usually enough time to accumulate a large attitude error, usually reaching the attitude deadband once before aerodynamic forces began to dominate the motion. By holding a constant speed on the MGS reaction wheels until the spacecraft was near periapsis, MGS eliminated one source of angle of attack error. MGS deliberately drove the reaction wheel speed to the "unloaded" value near periapsis in order to unload the wheels using aerodynamic torque rather than thruster propellant.

Both missions had to adapt existing control laws to the aerobraking phase. The Magellan spacecraft was already in orbit around Venus when it was decided to try aerobraking. Although the MGS spacecraft was designed with aerobraking in mind from the start, the on-board hardware and software were inherited from the Mars Observer mission, so existing algorithms were used wherever possible to minimize development costs. The error signal for both was based on a time varying reference attitude, which created a maximum acceptable timing error limit. A better approach for future aerobraking spacecraft would be to hold an inertial reference attitude until on-board sensing of atmospheric entry triggers a time varying attitude. (The time varying is only needed near the end of aerobraking, when the drag duration becomes large as the orbit becomes more circular.) Such an option would have eliminated the unnecessary timing error constraint that drove the requirement for daily or multiple uploads per day.

Flight Software:

The on-board sequencing philosophy was one of the biggest differences between the Magellan and the Mars Global Surveyor missions. The Magellan flight software was rewritten after the radar mapping was completed so that the on-board sequence of events was turned into an infinite loop rather than a list of commands that were executed once. This change to an infinite loop greatly reduced the workload on the operations team, which was down to a skeleton crew by this time. An infinite loop was possible for aerobraking because the same events in the orbit were repeated over and over starting with the cat-bed heater turn-on prior to the turn to the drag attitude that was required near periapsis. An infinite loop was desirable because it greatly reduced the number of commands that had to be sent to the spacecraft to a few tweaks to the timing to keep the on-board looper in synch with the actual time of periapsis. In fact, the looper could have been modified to partially automate the aerobraking process by keying the start of the next sequence to the observed time of the previous sequence, as sensed by the thermocouples on the solar panels. Even the maneuvers were built into the sequences. The only parameter that had to be uplinked to perform a maneuver was a flag to choose from one of six pre-canned maneuvers (3 magnitudes and two directions). Five of the six precanned maneuvers were actually used for the twelve periapsis corridor control orbit trim maneuvers. Unlike the MGS mission, the location of the Magellan apses did not change very much during the aerobraking phase, so a single pair of inertially opposite attitudes could be used for the entire aerobraking phase.

For MGS, each maneuver was a complete mini-sequence with a specific start time obtained from the latest Nav solution, and a specific burn duration and attitude quaternion. Although the size and/or attitude could have been recomputed for every maneuver, the MGS project chose to select maneuver durations and attitudes from a precomputed and pretested list of maneuvers in order to eliminate testing during the time between the decision to perform the maneuver and the actual maneuver. The argument of periapsis during the MGS aerobraking phase changed considerably, especially as the orbit became more circular. The maneuver directions in the table were indexed in ten degree increments of argument of periapsis. Although this approach meant that many unused maneuvers had to be pretested, it reduced some of the risk of performing an incorrect maneuver. In spite of these precautions, one of the maneuvers was performed twice in the same orbit, when a flight software update coincided with a maneuver. Since this occurred when the orbit period was still large, there was time to build and perform a special third maneuver in the same orbit to undo the effects of the unwanted second maneuver before the spacecraft passed through periapsis.

Although the MGS spacecraft structure, unlike Magellan, was designed for aerobraking, the flight software was inherited from the Mars Observer mission. The primary goal was to reuse the flight proven software wherever possible in order to minimize the cost and schedule impact. Since it was possible to fly the mission using traditional sequences that had to be built on the ground and uplinked to the spacecraft before the previous sequence "ran out" of commands, no money was spent to develop a Magellan style "looper" to minimize the workload on the operations team during flight. Since aerobraking operations were only supposed to take a few months, the additional operations workload seemed like a good way to save flight software development cost. Because the reference attitude was specified by a time varying set of polynomials, (also existing flight software), the upper bound on the timing error was about 225 seconds. Thus a new sequence of commands had to be built and uploaded before the timing error exceeded the 225 second timing error bound. (Exceeding the timing error by a few hundred seconds would have wasted propellant fighting the aerodynamic torques, but would not have been mission threatening.) Because the initial orbit period was so large, the orbit period was very sensitive to the drag. The largest period change in one orbit was 1.6 hours (5760 sec), so an atmospheric uncertainty of only 4% would be enough to wipe out any hope of predicting the next time of periapsis within the required accuracy, which meant that a new sequence had to be built and uploaded every orbit. Since the orbit initial period was nearly two days, it was possible for the operations team to build, validate, and upload a new sequence every orbit. As the orbit period shrank, the change in the orbit period per orbit also shrank. By the time the orbit was planned to reach 18 hours, the expected uncertainty in the atmospheric density coupled with the expected period change would have allowed a new sequence to be built every other orbit, such that only one sequence per day would be needed. For the very short orbits, as many as three sequences per day might have been required. What actually happened is that the mission had to be replanned and flown at a much lower dynamic pressure to prevent the broken solar "panel" from bending too far, which meant that the period change per orbit was smaller, and the operations team only had to build one sequence per day for most of the extended aerobraking phase. Had the MGS mission been able to aerobrake as aggressively as originally planned, as many as three uploads per day would have been required to keep the timing within limits. Combining a Magellan style infinite loop with an on-board sequence trigger based on acceleration measurements to determine the time of the previous periapsis could have reduced the number of uploads to once a month plus an upload each time a maneuver was required.

Navigation:

The Navigation teams provided essential measurements for both the Magellan[9, 10] and Mars Global Surveyor[22] missions. Both spacecraft were tracked almost every orbit during aerobraking and the two way coherent data were converted into estimates of the peak density during the previous drag pass as well as the updated orbital elements and predicted times for the coming periapses. The Navigation density estimates were the only way to obtain the density for the Magellan mission, so only the integrated effects of the drag could be measured. The density had to be inferred by assuming a constant value for the scale height, and then estimating the density that would give the integrated drag inferred from the change in the orbital elements. On the MGS mission, accelerometer data were also available, so the structure of the upper atmosphere along the flight path could be studied. During MGS Phase 1, which was during the dust storm season near perihelion, the atmosphere almost never looked like the smoothly varying exponential used in the computer simulations. The atmosphere contained waves, had variable scale heights at different altitudes, latitudes, and times, and infrequently even had very sharp unexpected changes in density of a factor of 2 in a matter of seconds. During MGS Phase 2, which was closer to aphelion, the atmosphere still had longitudinal waves that were correlated with the topography, but the atmosphere during most of the passes was much smoother and more like the predicted exponential atmosphere.

The Navigation tracking data were also used to improve estimates of the gravity fields of Venus and Mars. Just prior to the start of the Magellan aerobraking phase, the periapsis altitude was lowered to about 180 km for 8 months in order to collect data to improve the gravity field. In the middle of the MGS aerobraking phase, periapsis was raised out of the atmosphere to about 175 km for 5 and one-half months as part of a Science Phasing Orbit, where the project had to wait for the location of the Sun relative to the orbit to achieve the required geometry. Collection of gravity science data were one of the objectives during this low altitude orbit. As far as aerobraking is concerned, Venus and Mars are fundamentally different in two important respects. Venus rotates relative to the stars only once every 243 days, so the gravitational perturbations on one orbit are not very different from the next, so periapsis drifts up or down in a very smooth and predictable manner. On Mars, the gravity field is not nearly as uniform as on Venus, and the Mars rotates much faster, such that the spacecraft almost never flies over the same longitude twice in a row, so the perturbations on the spacecraft are stronger and different from orbit-to-orbit. This difference means that the periapsis altitude is constantly being perturbed up and down by hundreds of meters every orbit. Combining this with the fact that the Mars atmospheric density at the aerobraking altitudes around 110 km appears to be strongly correlated with the topography, means that the density at periapsis had about a 40% variability (1-$\sigma$) at Mars (30% due to the randomness of just the atmosphere). In contrast, the density at periapsis for Magellan had only about a 6% variability.

Atmospheric Differences:

One of the key differences between aerobraking at Venus and aerobraking at Mars is the margin required for atmospheric variability[23-25]. Although some data indicated that the atmosphere at Venus might be much more variable on the night side of the planet, the Magellan mission saw much less variability on the dayside (6%) than predicted (12% 1$\sigma$). In contrast, the Mars Global Surveyor mission expected very high variability in the atmosphere (35% 1$\sigma$ ) and experienced orbit-to-orbit variability of about that magnitude. A significant fraction of the orbit-to-orbit variability was correlated with the longitude of periapsis, i.e. with the topography of the surface, and this fact was used to schedule the periapsis corridor control orbit trim maneuvers to minimize the risk of experiencing a density that would be large enough to cause damage to the spacecraft. Unfortunately, the density at aerobraking altitudes in the Mars atmosphere appears to be even more sensitive to dust storms anywhere on the planet than previously thought. Since flying at a nominal density low enough to accommodate the worst possible dust storm without raising periapsis would stretch the duration of the aerobraking phase from a few months to many months, most missions fly at a nominal density low enough to accommodate the orbit-to-orbit variability, but require ground intervention to propulsively raise periapsis in response to the density increase that accompanies even a moderate dust storm near the surface. Thus Mars aerobraking mission operations must be continuously on the lookout for evidence of dust storms in order to be able to raise periapsis before the density increases enough to damage the spacecraft.

Mission Phase while Aerobraking:

Another key difference was the mission phase where aerobraking occurred. For Magellan, aerobraking occurred late in the extended mission where the hardware was nearing the end of its useful life. The project was down to a skeleton crew. If the Magellan spacecraft had crashed and burned during aerobraking, it would not have been viewed as a loss. Fortunately for all of the Mars Projects that followed Magellan, the Magellan aerobraking phase was successful in demonstrating that aerobraking was a viable way to extract energy from vehicles orbiting other planets. On the other hand, the Mars Global Surveyor spacecraft aerobraking phase occurred immediately following capture at Mars. If the MGS spacecraft had crashed and burned while aerobraking, it would have been viewed as a catestrophic loss of mission. The fact that the MGS spacecraft was successfully aerobraked into exactly the desired orbit, in spite of a seriously damaged solar "panel" is evidence not only of the robustness of aerobraking, but also the ingenuity and dedication of the Mars Surveyor Operations Project (MSOP) which was responsible for operating the spacecraft after launch.

SUMMARY:

Two interplanetary spacecraft have been aerobraked successfully at two different planets. Aerobraking has been shown to be a very robust technique that can be adapted to different spacecraft hardware and software. Future missions can take advantage of the lessons learned from these missions during the design and operation of the aerobraking phase.

The Magellan aerobraking phase was very exciting, because it was the first time that aerobraking had ever been tried at another planet. There was no guarantee that the spacecraft would survive. Fortunately, the aerobraking phase went according to plan and paved the way for using aerobraking on future missions.

The Mars Global Survey aerobraking phase was alsovery exciting, but for different reasons. One of the solar panels was damaged, and might have been torn off the spacecraft by the aerodynamic drag at any time. The mission had to be extensively redesigned during the 25 day hiatus just after the start of aerobraking to accommodate the reduced structural capability of the damaged panel. The first half of aerobraking coincided with the dust storm season on Mars, and a relatively small dust storm forced the project to raise periapsis in a hurry. Fortunately, the redesigned aerobraking phase successfully placed a fully operational spacecraft in the desired mapping orbit, and the mission is currently proceeding as planned, in spite of the one year delay in the start of mapping. In fact, some of the observations and scientific discoveries that were made during the science phasing orbit in the middle of aerobraking would not have been possible if the solar panels had deployed without incident.

A third mission, the Mars Climate Orbiter, is about to begin an aerobraking phase in September. It will be interesting to see what new lessons are learned from that mission.

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